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Potential challenges of integrating large-scale wind energy into the power grid–A review

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ABSTRACT

Global warming is attracting a growing interest worldwide for the generation of large-scale energy from renewable energy sources as it is free from greenhouse gas emissions. Wind energy is one of the most promising renewable energy sources due to its availability and low cost and due to the fact that it is more efficient and advanced in technology. Hence, harvesting of large-scale wind energy is of prime interest today. However, large-scale integration of wind energy sources creates environmental, economic, social and technical impacts that need to be investigated and mitigated as part of developing a sustainable power system for the future. Government, utilities and research communities are working together to increase penetration of wind energy into the power grid and overcome potential barriers associated with this. This paper presents an extensive and useful survey on wind energy technology and associated implementation issues including effects of wind farms on the nearby locality. This paper also reviews the social, environmental and cost-economic impacts of installing large-scale wind energy plants. Finally, potential technical challenges to the integration of large-scale wind energy into the power grid are reviewed in regard to current research with their available mitigation techniques.

Contents

1. Introduction

Current power systems create environmental impacts and are a leading cause of current greenhouse gas (GHG) or global warming effects due to burning of fossil fuels, especially coal, as

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carbon dioxide is emitted into the atmosphere [1,2]. According to the report of the International Energy Agency (IEA), the world's total net electricity consumption as well as electricity generation is increasing day by day. The world electricity generation was 14,781 billion kWh in 2003 and is projected to be 21,699 and 30,116 billion kWh in 2015 and 2030 respectively, an average increase rate of 2.7% annually [3,6]. GHG emissions from electricity generation are approximately 40% of total emissions as most of that industry uses fossil fuels, particularly coal and oil, hence are a leading contributor to global energy-related CO_2 emissions [3]. Australia's abundance of coal imposes environmental costs in the form of GHGs, including 200 million tons of carbon dioxide equivalents (CO_2-e) released from the energy sector in 2008, more than a third of Australia's total CO_2-e emissions [4]. The CO_2 emissions around the world are given in Fig. 1 [5].

A recent burning issue is to achieve environment-friendly, economical and sustainable power transmission and distribution systems that are intelligent, reliable and green. Therefore, policy makers, power system planners, researchers, and power utilities are working together worldwide to reduce GHG emissions and hence, in 1997, a treaty was formulated called the Kyoto Protocol [6]. The objective of the Kyoto Protocol is to reduce GHG emissions into the atmosphere to a level that would prevent dangerous anthropogenic interference with the climate system [6]. Renewable energy (RE), in particular wind energy is the most promising of the RE sources which are free from GHG emissions, and it has potential to meet the energy demand due to its availability which encourages interest worldwide. It is one of the fastest growing and cost-effective resources among the different RE sources that have begun to be used worldwide for sustainable climate-friendly power systems [7,8]. Over recent years there have been dramatic improvements in wind energy technologies, and wind is increasingly becoming an important energy source. Wind energy can be exploited in many parts of the world, but the determination of wind energy potential depends on the meteorological dimensions of the wind direction, velocity and solar irradiation [9].

Winds are caused due to the absorption of solar energy on the earth's surface and in the atmosphere, and the rotation of the earth about its axis and its motion around the Sun. A windmill converts the kinetic energy of moving air into mechanical energy that can be either used directly to run a machine or to run a generator to produce electricity [10,11]. Wind energy plays an active role in developing a climate-friendly environment and makes the world more livable for humans as well as for all living creatures. Both large-scale and small-scale energy can be produced from wind turbines for utilities, industries, home owners and remote villages [12].

Since the beginning of the development of the wind power industry in the 1980 s, the rated capacity of wind turbines has increased from some tens of kW to today's MW turbines. At the same time, the trend has moved from installations including a single or a few wind turbines to planning of large wind farms ranging from some tens of megawatts to over 100 MW. At the beginning, wind energy was introduced and its use expanded in some European countries including Germany, Denmark and Spain. However, its energy-efficiency, clean, pollution free and cost-effective attributes drew the attention of politicians, industrialists and individuals, and hence wind energy generation has been greatly encouraged worldwide [9].

Wind energy is the fastest emerging energy technology, and total cumulative installed capacity of wind energy in the world by 2000 was 17,400 MW, while in 2011 the cumulative installed capacity is 237,669 MW as shown in Fig. 2. Annual installed wind capacity in 2000 was only 3,760 MW; with rapid growth, annual installed capacity in 2011 was 40,564 MW. In 2010, the rate of increase of wind energy generation globally was 24.1%, though there had been a slight decrease in the growth rate than earlier due to the worldwide financial crisis [13]. By the end of 2011, 26.7% of worldwide wind energy capacity was installed in China, 19.7% in the USA, 12.2% in Germany, 9.3% in Spain and 6.8% in India. Worldwide wind energy installed capacities from these five countries totaled 74%, and the remaining 26% was installed throughout the rest of the world including Europe, Asia, North and South America and Australia. The rise in the Chinese wind sector has constantly outperformed other countries, and in 2011 they added 18 GW of new wind power, which was half of the total wind power installed worldwide in 2011 [13]. According to the

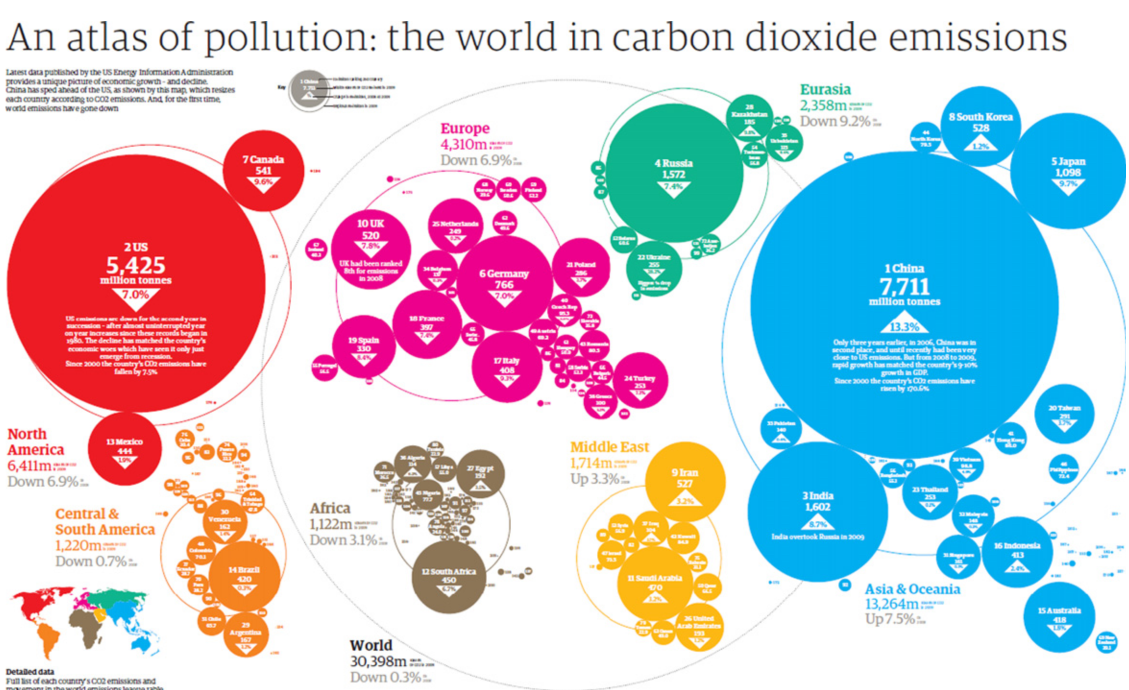


Fig. 1. Carbon dioxide emissions around the world [5].

Global Wind Energy Council, the growth rate of wind energy will increase rapidly and, over the five years to 2016, global wind capacity will rise to 493 GW from the 237 GW available at the end of 2011 as shown in Fig. 2. While the capacity installed in 2011 was 40.6 GW, the capacity predicted to be installed in 2016 is 59.24 GW; hence the projected annual growth rates during this period will average 13.65% [13].

Australia has been slow to adopt wind energy to the extent that Europe has; however, in Australia there are several large wind farms that have been commissioned or are in advanced stages of planning. In particular, after implementation of the national Renewable Energy Target (RET) in January 2010 with the mandate of generating 20% or 45 TWh of Australia's electricity supply from renewable energy sources by 2020, Australia has taken a wide range of initiatives to install large-scale wind energy plants around the country. South Australia is the most promising State for wind energy generation considering wind speed, generation and transportation costs. Northern Queensland has good wind resources, especially during the winter "south-east trade wind" season [11]. Victoria and the west coast of Tasmania also have wind energy potentialities. In 2010, Australia's total installed capacity of wind energy was 1880 MW, this being an increase of 167 MW from 2009. Currently there are 52 wind farms, mostly located in South Australia (907 MW) and Victoria (428 MW). In the last decade, the growth rate of wind energy production was 30% annually on average [13]. State-wise wind energy installed capacity is given in Fig. 3.

Large-scale generation of wind energy reduces the energy crisis and releases the pressure on other sources. However, there are number of potential challenges that need to be considered when installing large-scale wind energy plants for a sustainable power system. There are negative environmental impacts due to installation and operation of the wind farms that affect the living practices of the local population, i.e., visual impacts, noise and death of wildlife due to the presence and operation of the wind turbines. These effects may be minor but need to be considered as they persist for a long time and directly affect the nearby locality. One of the negative impacts of wind energy generation is its high costs due to the installation and operation costs. The major costs involved in wind energy generation are: capital costs including wind turbines, foundations, transportation, road construction and grid connexion; and variable costs including operation and maintenance, land acquisition, insurance and taxes, management and administration. It is well known that wind energy is free from GHG emissions; however, there are minor emissions during the manufacturing and future dismantling of wind farms which

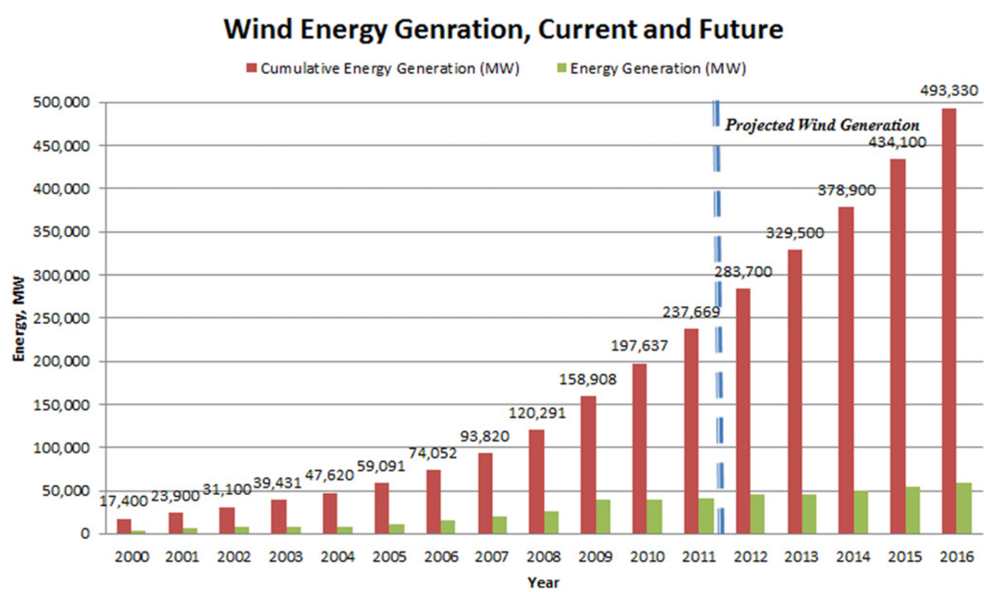


Fig. 2. Global wind energy installed capacity, current and projected.

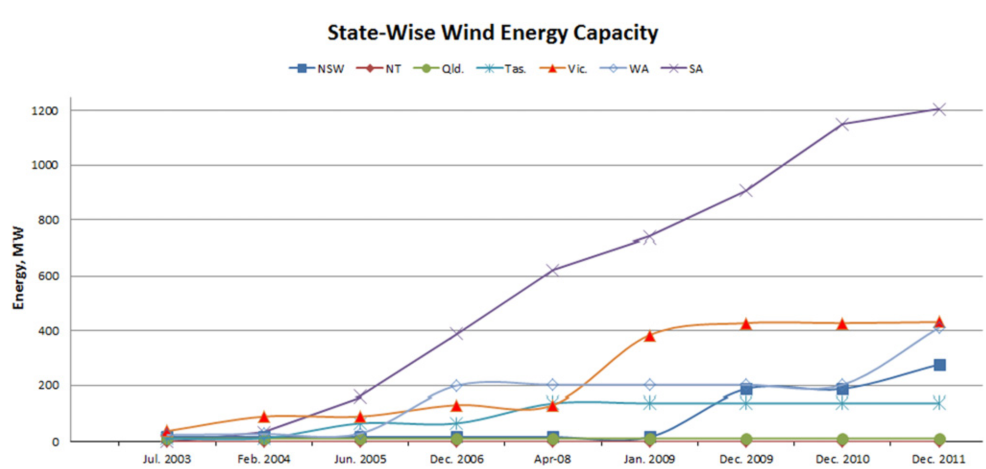


Fig. 3. State-wise installed wind energy capacity in Australia.

create environmental impacts and need to be considered when constructing a wind energy farm. A Life Cycle Assessment (LCA) process is widely used to investigate environmental impacts [14–17]. The negative impacts on the environment and cost-economic analysis of wind energy generation are essential to be further studied for a sustainable power system for the future. Research communities are investigating the environmental impacts from different points of view, and their findings are available for the power utilities and manufacturers to take into account in their decision making before constructing a wind farm. Researchers have also evaluated the economic cost of wind energy generation and concluded that the wind energy price is comparable with other energy sources, and better than other options after considering emission costs. This study further explores the available research on these areas and makes a concrete conclusion which is available to utilities for further action to develop wind energy plants for the future.

Integration of wind energy into the grid also creates potential technical challenges that affect power quality (PQ) of the systems due to the intermittent nature of wind energy. With the increased penetration of renewable energy into the grid, the key technical potential challenges that affect quality of power include: voltage fluctuation, power system transients and harmonics, reactive power, electromagnetic interference, switching actions, synchronisation, long transmission lines, low power factor, storage system, load management, and forecasting and scheduling [18–20]. Therefore, there is a prime need today to reduce these potential technical challenges for a successful integration of large-scale wind energy into the grid, though it is not an easy task. Researchers are working to explore these problems with potential mitigation techniques. There are many studies available today that elaborate on the problems individually with appropriate alleviation techniques using both simulation and experimental analysis. However, there is no precise study that explores or reviews all of the problems with their mitigation techniques. Therefore, this study has presented a comprehensive and useful survey on the technical challenges and their associated alleviation techniques that researchers, utilities and industries are expected to use for further integration of large-scale wind energy integration into the energy mix.

2. Social Impacts

Wind energy is the most environment-friendly, energy-efficient, cost-efficient and 100% clean energy resource, and hence wind energy has begun to be used as the panacea for solving global warming. There is an increasing interest worldwide for the introduction of large-scale wind energy into the energy mix for a sustainable environment-friendly power system for the future. However, along with the positive impacts, it also has some negative impacts on the environment as well as human life. The most substantial negative impacts that affect human living culture are visual impacts, noise and killing of wildlife. Among these, visual impacts and noise are a direct disturbance for the local community, and hence the acceptance/attitude of the nearby community is an important factor. Another problem is interference of turbine equipment with radar or television that disturbs the signal strength. With time, public attitude towards wind energy generation is improving while manufacturers are also improving their technologies to reduce noise levels and improve aesthetic views [14,15]. The most common environmental impacts that affect social life are presented in Fig. 4.

Visual impact depends on shape, colour and layout of the wind turbines, distances from the inhabited locality, shadow flickering and the location of the wind energy plant [14,21]. However,

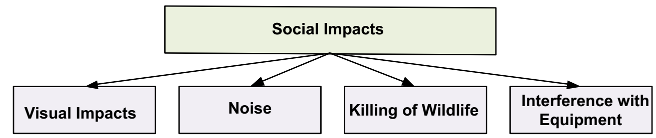


Fig. 4. Potential social impacts from large-scale wind turbine installations.

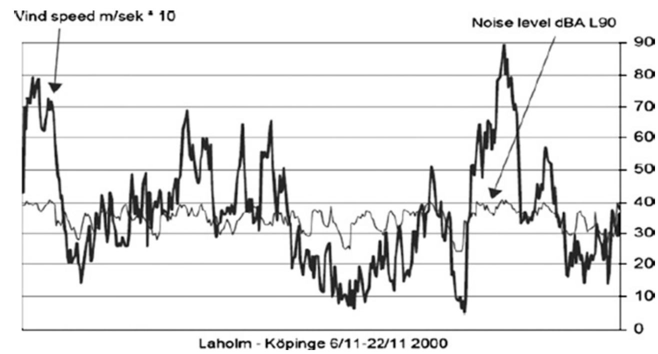


Fig. 5. Comparison of wind speed and noise level in dBA L_{90} [33].

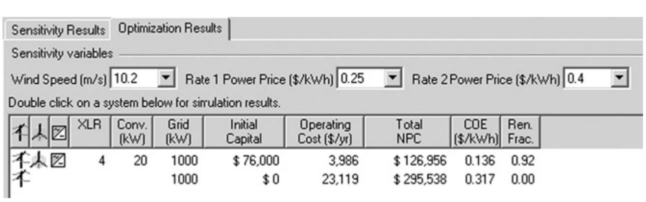
reactions to this problem depend on individual perceptions which are difficult to measure. Arranging same-size turbines in simple and uniform rows and using columns with light colours may help improve people's perceptions of the aesthetics of wind farm installations [22]. In a study by Gourlay [23], it was found that 70% of people in the UK had a positive attitude regarding visual impacts and thought wind turbines were impressive and nice. On the other hand, tourism officials had a negative attitude as they thought wind turbines would decrease local tourism [24]. The Quechee Test, Multicriteria Analysis (MCA) and the Spanish method have been used to analyse visual impacts considering different scenarios that include: whether the wind turbine could cause an adverse aesthetic impact on the landscape; MCA analysis with physical attributes (such as water, land, snow, etc,) and aesthetic attributes (such as colour, texture, etc.); and quantification of potential visual impact. Results show that, the higher the value of physical attributes, the deeper the impact level, and also that the mitigation of potential visual impacts improves the public acceptance of the innovation [25–28].

It was observed from the study [29], that turbines in operation cause less visual impacts compared to stationary turbines as the blades are invisible when rotating. Shadow flicker produced by moving blades and the reflection of the sun's rays from the wind turbine causes disturbance for residents living nearby. This is not a major problem as wind turbines are relatively small. However, an inhabited locality should be protected from the shadow effect. This can be reduced by optimising the rotor blade surface smoothness and coating the turbine with a material having less reflective properties [15,30].

The most common noise from a wind turbine is mechanical noise which is emitted by the gear box, electrical generator and bearings. Normal wear and tear, poor component design and lack of preventive maintenance are also causes of mechanical noise [31]. Flow of air passing through the turbine blades causes aerodynamic noise which increases with the speed of the rotor [32]. A study by Bjorkman [33] has shown that wind turbine noise is independent of wind speed for distances greater than 300 m from the turbine as shown in Fig. 5. The figure shows the wind speed as function of time plotted together with the A-weighted sound level in a site 300 m far from the wind turbine. Noise pollution directly affects nearby communities; excessive noise causes sleeping disturbance, hearing loss, disruption of the vestibular system (affecting balance, orientation and movement)

and serious discomfort to ill people [34]. The effect of noise pollution also reduces the value of property and locality. Therefore, turbines should be kept to a minimum noise level that does not affect the community greatly. Research suggests that wind turbines should be built at least 2 km away from inhabited locations and be surrounded by sound proofing systems that minimise noise emissions [35]. Mechanical noise should be minimised at the turbine design stage including by using acoustic insulation on the inside of the turbine housing. Acoustic insulation curtains and anti vibration support footings can also be used to reduce mechanical noise [36]. Aerodynamic noise can be reduced by careful design of the blades [36]. Son et al. [37] developed an integrated numerical method based on Ray theory and observed that aerodynamic noise can be significantly reduced by using obstacles in the propagation path. Use of optimised blades or scattered blades can reduce the noise level by, on average, 0.5 and 3.2 dB respectively [38].

Large-scale wind energy generation plants are harmful to wildlife; however the impacts are smaller compared to other sources of energy. Sovacool estimated that fossil fuelled power stations killed twenty times more birds than wind turbines per GWh [39]. The direct impact is the death from collision with the wind hub and blades as well as during wind plant installation activity. Avoidance, habitat disruption and displacement cause indirect impacts [40]. Turbines with lower hub heights and shorter rotor diameter cause the blades to spin at high RPM, and combined with tighter turbine spacing's compared to typical newer wind turbines, have the potential to kill a larger number of birds [40]. As birds are the largest victim groups, it is an issue of concern to many bird lovers today. However, this effect is minor as the local birds can easily cope with and avoid the obstacles [41]. Research shows that birds killed by wind turbines are a negligible proportion compared to deaths of birds caused by other human activities such as urbanisation [25]. In a study, it was found that number of birds killed in a year is 20, 1500 and 2000 respectively from wind turbines, hunters and collision with vehicles and electricity transmission [15]. However, to increase wind energy penetration it is essential to reduce the negative impacts on wildlife due to wind turbines. It is possible to reduce the impacts on wildlife through proper design and planning [42].



XLR	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
4	20	1000	$ 76,000	3,986	$ 126,956	0.136	0.92
		1000	$ 0	23,119	$ 295,538	0.317	0.00

Fig. 6. Optimisation results with wind speed (10.2 m/s), and grid electricity price (rate 1: $0.25/kWh, and rate 2: $0.4/kWh) [46].

The newly developed turbines with tubular steel towers that have smooth exteriors (rather than lattice towers) can prevent the nesting of birds [15]. Vertical shaft turbines are safer and produce twice the energy of prop-style turbine [43]. Avian radars are used in a project in Texas to detect birds in an area which is on their migration path. If there is any possible risk to passing birds, the system will immediately stop the wind turbines and start again when the birds cross the wind farm safely [44]. In order to understand the breeding and feeding behaviours of birds, professional wildlife surveys may be carried out to identify actions that minimise the risk imposed on the birds [45].

3. Economic Impacts

Wind energy has significant potentialities due to its availability, climate-friendly and energy-efficient features and is expected to play a major role in the future energy sector. However, it is necessary to make financial sacrifices today to fund the high upfront cost of wind energy generation to achieve a sustainable pollution free society for the future. Economic costs of hybrid systems have been investigated by the current authors in a recent study [46] in which wind/grid-connected and grid-connected only systems were evaluated. The optimisation results for Macquarie Island, Tasmania, Australia for a specific wind speed (10.2 m/s) and two grid electricity prices (rate 1: $0.25/kWh, and rate 2: $0.4/kWh) are illustrated in Fig. 6. From this figure it can be seen that, in a wind/grid-connected system, the cost of energy is only $0.136/kWh as 92% of the total energy is produced from wind energy, while the cost of energy in a grid-connected only system is $0.317/kWh. This study estimate the cost depends only turbine purchase costs, however, does not focus on wind plant installation cost, transmission cost, and other variable costs [46].

Therefore, to estimate an accurate cost of wind energy generation, the key factors that need to considered are: capital costs, operation and maintenance costs, generation costs with respect to wind availability and the economic lifetime of the total financial investment. Costs of wind turbines, transportation, civil works, road construction, installation, grid connexion and development and engineering are the capital cost which comprises the major part of the total cost of the plant. Operation and maintenance (O&M) is the continuing process required for the smooth operation of the plant after installation; this includes monitoring of the system, repair and maintenance of the system, spare parts, land and sub-station rental, insurance and taxes, management of the system and advisory tools to monitor the system. Another significant factor is the variable cost of generation due to variable wind resources as wind energy generation is mostly dependent on wind speed. Costs of wind energy generation from different processes are given in Fig. 7. Turbine specifications and site characteristics are also critical in determining generation costs.

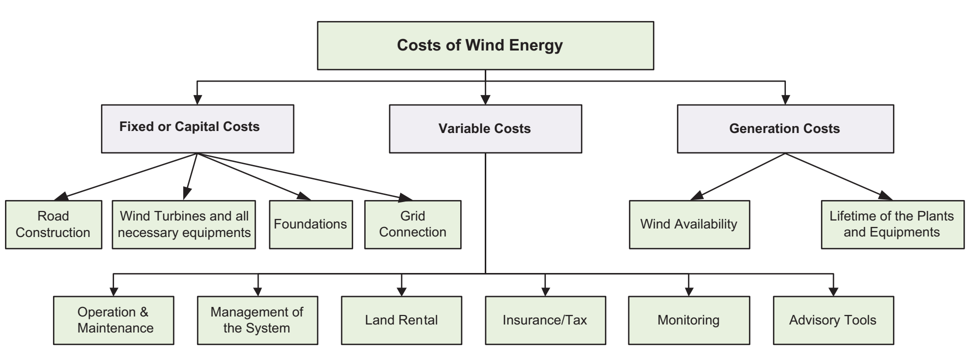


Fig. 7. Costs of large-scale wind energy generation.

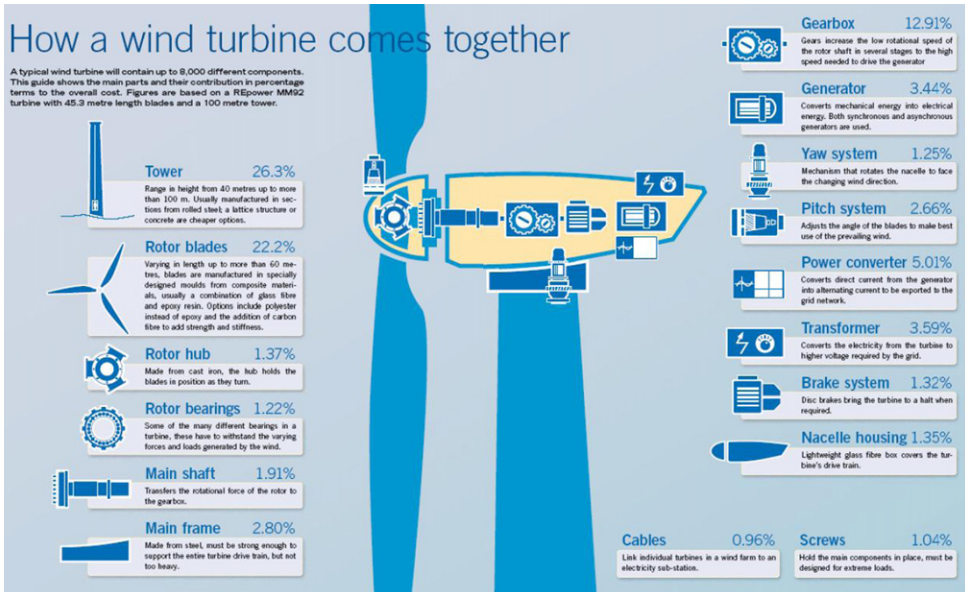


Fig. 8. Main components of a wind turbine and their share of the overall cost [16].

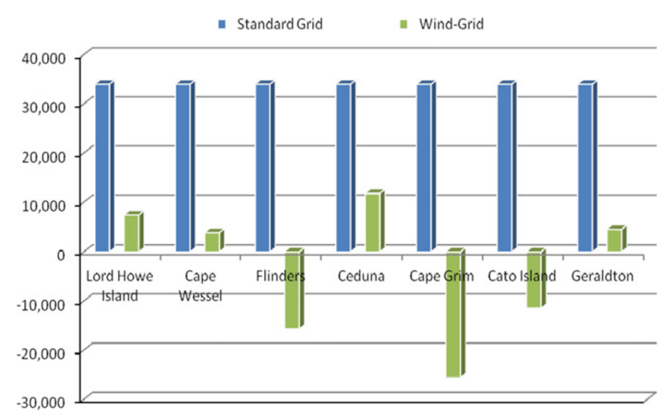


Fig. 9. Emissions analysis of standard grid-connected and wind/grid-connected systems for selected Australian locations [46].

O&M costs also depend on size, quality and age of the turbines and other associated equipment [14,16]. Wind energy plants require huge capital investment due to their large capital costs. Most developers don't feel interest to invest in wind energy plant due to the lack of financial ability. Therefore, research has been and will continue to be undertaken to reduce the capital costs by reducing costs of equipment, transportation costs and civil works. Over time, reduction of O&M costs have been achieved by using new turbine technology, and developing monitoring software that reduces maintenance and repairing costs; it is crucial that these efforts continue.

Blanco [16] made an analysis for the capital and O&M costs separately, and carried out a sensitivity analysis of the generation costs based on capacity factor, capital costs, O&M costs, interest rate, etc. That study also estimated the cost of wind energy generation both for onshore and offshore wind farms and compared those with the cost of energy generation from other sources of energy. The major components of a wind turbine and their share of the overall wind energy generation cost are given in Fig. 8 [16]. Based on the study, the energy generation cost from an onshore wind plant is between 4.5 and 8.7 €cents/kWh, and the cause of the large variation in these prices is the availability of the wind resource. However, the per unit generation cost of energy is relatively lower for natural gas, coal and nuclear energy which were 4.9, 4.1 and 6.6 €cents/kWh respectively in 2007. The most useful features of wind energy are the absence of GHG emissions and its abundance worldwide for meeting the energy crisis [16,47]. Blanco and Rodrigues [48] have shown that the inclusion of a CO_2 price of around 30 euros/ton would make wind energy the least-cost option.

From long-term prediction modelling, it has been seen that the cost of wind energy generation has reduced significantly with time. A wind turbine generates 180 times more electricity at less than half the cost per kilo watt hour today than its equivalent 20 years ago [49]. A report of the European Commission in 2007 indicated that the capital cost of wind energy is likely to fall to around 826 €/kW by 2020, 788 €/kW by 2030 and 762 €/kW by 2050 [50]. Another study by the British Department for Business, Enterprise and Regulatory Reform [51] predicted an increasing trend of wind energy cost until 2020 after which the cost will start reducing. It has also been seen that the capital costs of new installations dropped from around $1500/kW for 1650 kW turbines in 1989 to about $800/kW in 2000 for machines rated at 1650 kW [52]. With the development of innovative new technology, it is possible to reduce the price of turbines and associated equipment and integration techniques by using smart grid technology and forecasting models to know about the exact scenario of wind resources that will make wind energy more competitive and cost-effective for the future.

4. Environmental impacts

A recent study by Shafiullah et al. [46] has shown that wind energy has a role as a promising energy source as it is free from GHG emissions. In their study, these authors estimated the total yearly emissions of CO_2, SO_2, and NO_2 from standard grid-connected and wind/grid-connected systems for seven locations in Australia that have significant wind energy potentialities. In Fig. 9, for Ceduna in South Australia, the standard grid-connected only system emitted 34,018 kg CO_2 annually, while a wind-grid-connected system emitted only 11,773 kg/year. Fig. 9 also shows that a few places have negative emissions for a wind-grid system, indicating that this system generates more power than is used locally, and therefore has surplus electricity which can be input to the grid.

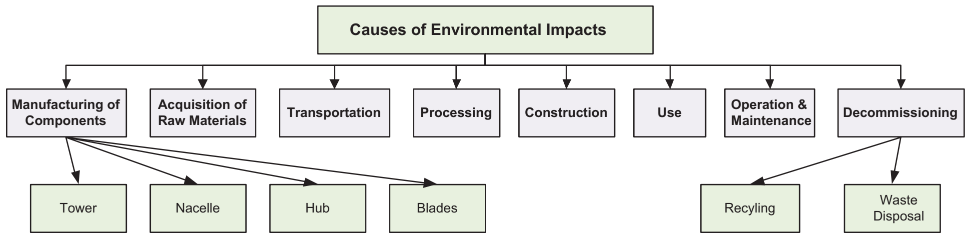


Fig. 10. Stages of environmental impact analysis through LCA.

Shafiullah et al. [46] only considered the emissions produced during generation of wind energy, not the emissions produced during manufacturing, installing and future dismantling of a wind turbine. The emissions produced from a wind turbines cradle to grave existence are [17]: manufacturing of components (tower, nacelle, hub, blades, etc.), acquisition of raw materials, transportation, processing, construction, installation, grid connexion, operation and maintenance, plus dismantling and waste disposal as shown in Fig. 10. Therefore, to know the exact environmental impacts from wind energy power generation, a rigorous LCA process that considers all the phases of a wind turbine's life cycle from raw material acquisition to disposal are required.

Martinez et al. [17] proposed an LCA model that evaluates the wind energy and emissions produced from current wind energy production technology by analysing a 2 MW wind turbine during its complete life cycle. From the study, it was observed that the manufacturing stage greatly affected the environment. In particular, the foundation has the greatest impacts on the environment, mostly due to the emission of particle materials during the cement making process [17]. It was also noted that the environmental impact of constructing the tower mostly depends on the quality and type of the materials and the welding process used. The study concluded that the annual impact of a wind turbine is close to four Eco-points, while the environmental impact of an average European citizen is equal to 100 Eco-Indicator points [53]. Environmental impacts from wind will be less than from other conventional sources if the wind turbine exists for at least twenty years. Appropriate evaluation of the decommissioning phase and the recycling of the turbine can reduce environmental impacts. The recovery of environmental resources in the recycling process from the tower, nacelle, rotor and foundation are 52%, 31%, 10% and 7% respectively. It can be concluded from the study that the environmental impact can be reduced during the manufacturing stages by careful design of the turbine and its components. Manufacturers can use LCA analysis as a guideline to optimise their products and quality to obtain an eco-label [54,55]. However, these authors did not focus on environmental impacts due to transportation in any great detail.

A comprehensive study has been conducted by Tremeac and Meunier [56] that analysed all life cycle stages of wind turbines and performed LCA analyses both for small-scale (250 W) and large-scale (4.5 MW) wind turbines. From the study, it was shown that wind energy is an excellent environmental solution under the following conditions: a high efficiency turbine designed and installed at a site with good wind speed, with transportation costs kept to a minimum and recycling performed appropriately at the end of the turbine's life cycle. The construction phase is responsible for the highest environmental impact, while the transportation and operation phases are categorised as second and third in level of impact. A huge impact was found for human health in the transporting of equipment during construction and decommissioning, reaching 44% of the total health impacts for the 4.5 MW turbines. However, this impact was assessed as being much less for 250 W turbines as it was assumed possible to transfer the smaller equipment involved by boat instead of trucks. Emissions from trucks are the main reason for the high impacts from transport; transportation by boat and train is preferable to the use of trucks.

It can be concluded that, compared to other sources of energy, wind energy has less negative environmental impacts. Moreover, its wide availability helps reduce the energy crisis worldwide as well as cut dependency on energy imports; this, together with the potential employment opportunities that come with the new technology, makes it the most prominent energy resource today. Therefore, it is of fundamental importance to be able to bring higher percentages of wind energy into the energy mix; accordingly, Government, research communities and industries are working together to achieve this critical objective. However, integration of large-scale wind energy with adequate power quality into the grid is a challenging task due to the intermittent nature of wind which is explored in the next section.

5. Potential technical impacts on power quality

Issues that need to be considered to integrate large-scale wind energy with the power grid are efficiency, reliability and power quality (PQ), power imbalance, cost of the energy conversion, power system operating cost, appropriate load management, safety and security [57–58]. The integration of variable generation sources presents unique challenges on system performance, and the key factors include [18,58]:

- RE generator design parameters and power movers' type
- RE power generation's expected types of run
- the position of the RE plant's connexion to the grid
- nature of wind variations and turbulence across a wind farm site
- interaction with other RE sources
- the characteristics of the grid including the loads connected to it.

In the next subsection, the influence of generator design and wind turbine types on large-scale integration of wind energy into the energy mix has been presented.

5.1. Impacts of wind generator/turbine technology

The wind farm is composed of several wind turbines which have basic electrical components: an aerodynamic rotor, a mechanical transmission system, an electric generator, a control system, limited reactive power compensation and a step-up transformer as shown in Fig. 11. The generator is used for converting the mechanical power obtained from the wind turbine to electrical power. A wind turbine comprises rotor/blades for conversion of wind energy into rotational shaft energy, a nacelle with drive train that contains the generator and gear box, a tower that supports the rotor and drive train and the necessary electric equipment for connexion to the grid. The majority of wind turbines offered today are of the three-bladed upwind horizontal

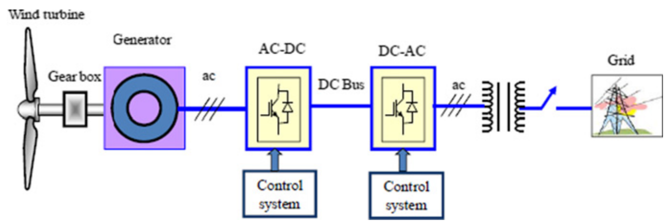


Fig. 11. Grid-connected wind energy system [59].

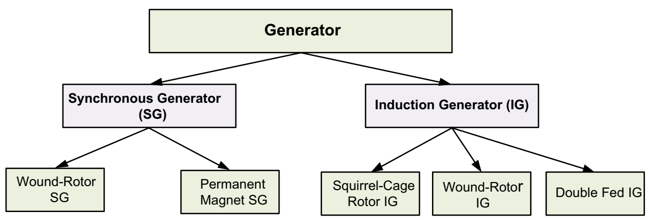


Fig. 12. Commonly used generators in wind turbines/farms.

axis type complete with support structure, control system and electric installations intended for the point of common coupling (PCC) at medium or high voltage [10,59].

The energy conversion of the most modern wind turbines is done using fixed-speed machines (often with the capability to operate at two different, but constant, speeds) and variable speed machines. In fixed-speed wind turbine systems, the generation is directly connected to the main grid in a simpler way, and the frequency of the grid determines the rotational speeds of the generator and rotor [59]. A synchronous generator running with synchronous speed offers good power regulation, quality and higher efficiency. Wound-rotor and permanent magnet synchronous generators are the most popular type of synchronous generators used in wind farms [60]. The advantages of variable speed wind turbines are: able to capture maximum energy and system efficiency from the wind over a wide range of wind speeds, operate at maximum power point, reduced mechanical stress and improved power quality [61]. Induction generators are most popular nowadays due to their simple, inexpensive, rugged, and low maintenance features. However, they require high starting currents and reactive power from the grid during operation [62]. The types of induction generators used in wind turbines employ squirrel-cage rotor machines, wound-rotor machines (with controllable rotor resistance to change the slip) and doubly-fed induction generators (DFIGs). Asynchronous or induction generators require power factor correction capacitors to start the generator and allow the wind farm to operate close to unity power factor. Reactive power will be injected if the capacitors are switched off after starting the wind farm, that is use to maintain a uniform voltage profile on the network. However, this is also responsible for a poor power factor condition on the remainder of the network and generates voltage control problems [63]. Fig. 12 shows the most common types of generator used in wind farm systems.

Fixed-speed wind turbines driven by squirrel-cage induction generators are well-known because of their simplicity, durability and reasonable prices. However, control of active power is a challenging task as they cannot provide active power and hence, producing fluctuating electrical power due to wind speed variation [63]. This will lead to exceeding the standards of the power ramp rate which affects the system stability and frequency deviation at large-scale wind penetration levels [64,65]. The reactive power demand of these generators also fluctuates as the active power generation of the wind power has fluctuated in the induction generators. The active and reactive power variations cause voltage fluctuation at the PCC that can result in severe electrical malfunction or disturbances on utility power grids [66].

On the other hand, DFIGs are widely used in wind energy harvesting systems due to their reduced-size power converter, flexibility in autonomous control of the active and reactive power, and relatively simple and rugged structure. Voltage unbalance and system harmonics can worsen the performance of DFIGs by introducing unwanted torque harmonics and inaccuracy in the generation of commanded active/reactive power [67]. Usually, wind energy farms are located in rural areas with a weak local network or relatively long transmission lines; the presence of voltage unbalance has created a major problem in the performance of DFIGs. Introduction of small wind turbines in suburban and downtown areas over the past few years has elevated the possibility of system harmonics at DFIG terminals. The authors provide a system analysis and an in-depth electromagnetic evaluation of a DFIG system under the aforementioned conditions [67].

Recently, permanent magnet synchronous generators (PMSGs) have received much attention in wind energy application because of several advantages such as higher efficiency, increased energy capture and smaller size. PMSGs can be designed with a higher number of poles and hence a low speed gearless (direct drive) operation is possible [61,68] which reduces the cost significantly. A full rated power electronic converter is required to interface the power grid with the generator, which increases the power loss in the converter system. Abdullah et al. [69], focused recently developed a maximum power point tracking (MPPT) algorithm that locates and controls maximum peak of PMSG and other generators variable speeds. Authors also explore three selected control methods in terms of efficiency and speed of responses and it was observed that optimal torque control (OTC) method is superior to the other methods in terms of simplicity and accuracy [69].

Therefore, it can be concluded that the major PQ problems encountered in wind farms due to the design variations of wind turbines are [70–72]:

- uncontrollable reactive power consumption and low power factor
- variations of wind speed cause power fluctuations on the grid
- in a weak grid, power fluctuations cause severe voltage fluctuations as well as significant line losses.
- injection of harmonics into the grid which may potentially create voltage distortion problems.

Potential technical difficulties not only occur due to the design of wind turbine types but also due to the intermittent nature of the wind source, electrical equipment and the grid connexion characteristics, and also grid quality issues [72]. The interactions among the wind turbine, the power network and the capacitor compensation are essential aspects of wind generation to optimise reactive power as well as active power, power factor and harmonic impacts. The usual practice is to compensate reactive power locally at the wind turbine and at the PCC where the wind farm interfaces with the grid. For synchronous and asynchronous generators, reactive power control is achieved respectively by excitation control and through capacitor switching. In DFIGs, the power factor and voltage control is provided by the DFIGs ac/dc and dc/ac converters and controller [63,71,72]. Developments in turbine technology have allowed harnessing more energy from the wind by improving the turbine height and increasing the swept area with larger blade sizes. Improved blade design has allowed the harvesting of very low and very high wind speeds, and also increasing the amount of power per swept area [49].

The next subsection explores the potential technical difficulties observed on integrating large-scale wind energy into the

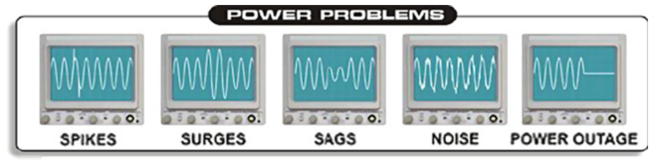


Fig. 13. Common problems related to voltage fluctuations.

energy mix due to the characteristics of turbines, the intermittent nature of wind resource, control system and grid connexion.

5.2. Power quality problems and challenges

With increased penetration of wind energy to the grid, the key potential technical challenges that affect quality of power observed include: voltage fluctuation, power system transients and harmonics, reactive power, electromagnetic interference, switching actions, synchronisation, long transmission lines, low power factor, energy storage system, load management, and forecasting and scheduling [18–20,57].

5.2.1. Voltage fluctuation

Voltage fluctuation or instability as well as voltage sags/dips, noise, surges/spikes and power outages are the common problems encountered during integration of large-scale wind energy into the grid as shown in Fig. 13. Variability of wind speed with time is not the only reason for these problems; grid connexion issues, faults during operations and starting of large motors, etc., are also responsible. The voltage stability in power systems can be classified as either slow dynamic or transient situations. Slow dynamic stability is related to a slow increase in load on the power system and deals with the reactive and active power supply. Transient voltage stability problems arise with sudden major power system changes, and have been related particularly to large-scale integration of wind turbines. Large penetration of wind power can lead to problems with the voltage control or the stability of power systems [8,10,73]. The voltage fluctuation or flicker caused by one machine varies inversely with the fault level at the point of grid connexion, therefore is a significant issue for weak grids. Voltage fluctuations disturb sensitive electric and electronic equipment which leads to a great reduction in the life span of that equipment [74]. Periodic disturbances to the network voltage are denoted as flicker. The level of flicker is quantified by the short-term flicker severity value P_{st}, and allowable voltage change as a function of frequency is $P_{st}=1$ [19,58]. Like voltage sag, the concerns associated with flicker are also related to voltage variations. In most cases, voltage flicker consists of periodic voltage fluctuations with frequencies of less than about 30–35 Hz that are small in size. Research shows that flicker emission from variable speed turbines is low compared to flicker emission from fixed-speed turbines [75].

5.2.2. Reactive power compensation

The consumption of reactive power by induction generators is a common problem which affects the grid PQ. An induction generator requires an increasing amount of reactive power as the amount of power generated increases, and it is essential to provide reactive power locally as close as possible to the demand levels. Due to the fluctuations in the active and reactive power, the voltage at PCCs fluctuates. The most widely used reactive power compensation is capacitor compensation, which is static, low cost and readily available in different sizes [19,74,76]. Reactive power compensation is typically implemented by using a fixed capacitor, a switched capacitor or a static compensator [72]. The power factor of the wind turbine can be improved significantly by appropriate compensation that enhances overall efficiency and voltage regulation of the system. Precise reactive power compensation considering proper size and proper control can remove voltage collapse and instability of the power system and enhances the overall operation of wind turbines.

5.2.3. Harmonic distortion

Power electronic devices, together with operation of non-linear appliances, inject harmonics into the grid which may potentially create voltage distortion problems. Operating harmonics need to be minimised to keep the total harmonic distortion within acceptable limits. There are no harmonics in fixed-speed wind turbines as there are no power electronic converters used. A small amount of harmonics is produced during the starting up of the turbines. However, wind turbines with converters inject harmonics into the network during their operation. Design of power electronic converters and filters are the influencing factors of harmonics produced by wind turbines [74]. Harmonic distortion can be minimised by good control algorithm design in the current control loop. Different types of filters are also used to mitigate harmonic distortion. According to the IEEE standard, harmonics in the power system should be limited for both the harmonic current that a user can inject into the network at the PCC, and the harmonic voltage that the utility can supply to any customer at the PCC [18,77].

5.2.4. Energy storage

Energy storage is essential in ensuring the reliability of power delivery. As RE sources have instability and uncertainty in their production, a storage system is useful as it can store excess energy and provide power when energy shortages occur. Integration of large-scale storage technology with the RE grid can ensure PQ and uniform power delivery. The existing energy storing technologies include batteries, flywheels, super-capacitors and superconducting magnetic energy storage (SMES) [18,19]. Integration of large-scale storage technology with the connexion of RE sources to the grid can ensure PQ and uniform power delivery. But the ancillary components (converters, filters, controllers, etc.) with the storage system have some effect on the overall power system. Integrating an energy storage system into a wind farm can eliminate or minimise some of the challenges associated with the wind energy integration. An energy storage system is required in a wind energy integration system to solve the problems of peak demand loading, wind fluctuations and system dynamic behaviour [59].

5.2.5. Load demand management system

Due to the intermittent nature of RE sources, appropriate planning and management of load demand is essential to ensure adequate PQ and uniform supply to the power systems. The inherent mismatch between the sources output and the load may lead to significant energy wastage. However, the contribution of wind power will vary over time based on wind speed. Thus, in high wind periods, excess power may have to be dumped. Accurate forecasting is essential for appropriate and satisfactory use of renewable sources, and to establish sustainable load management systems for the smart grid. Therefore, a load demand management system is required to maintain appropriate power supply which increases overall efficiency and quality of the system. Several research studies have been undertaken to assess the effects of wind speed, as well as production of energy from RE sources [18,73,78].

5.2.6. Synchronisation

Synchronisation of grid frequency, voltage and phase is a promising research challenge to control PQ. The most popular grid synchronisation method is based on a phase-locked loop (PLL) mechanism. Other techniques for synchronisation include detecting the zero crossing of the grid voltages or using combinations of filters coupled with a non-linear transformation. Four conditions which must be met for the wind-grid integration are: the wind power frequency must be as close as possible to the grid frequency; terminal voltage magnitude must match that of the grid; phase-sequence of the two three-phase voltages must be the same; and phase angle between the two voltages must be within 5% [8,19].

For a sustainable robust power system, it is essential to measure the observed potential challenges to ensure smooth operation of the power system network. Guidelines are developed to measure PQ parameters such as voltage fluctuations/flickering, harmonics, power factor, reactive and real power in the wind turbine as well as at the PCC. International standards are developed by the International Electrotechnical Commission (IEC) and other organisations to monitor the PQ parameters which are explored in the next subsection.

5.3. Compatible standard

The voltage fluctuations, reactive power compensation, poor power factor and harmonics distortion are the main aspects of power quality problems in integrating wind energy with the smart power grid due to the inherent characteristics of these resources as shown in Fig. 14.

IEC Standard 61000-4-15 [79] provides a functional and design specification for flicker measuring instruments to measure the correct flicker perception level for all practical voltage fluctuation waveforms. The flickermeter architecture is divided into two main parts, each performing one of the following tasks [79]:

- simulation of the response of the lamp–eye–brain chain
- on-line statistical analysis of the flicker signal and presentation of the results.

The short-term flicker severity based on an observation period $T_{st}=10$ min is denoted as P_{st} and is calculated using a multipoint method expressed by Eq. (1):

$$P_{st} = \sqrt{0.0314P_{0.1}+0.0525P_{1s}+0.0657P_{3s}+0.28P_{10s}+0.08P_{50s}} \tag{1}$$

where the percentiles $P_{0.1}$, P_1, P_3, P_{10} and P_{50} are the flicker levels exceeded for 0.1%, 1%, 3%, 10% and 50% respectively of the time during the observation period and suffix *s* in the formula indicates that the smoothed value should be used.

The short-term flicker severity evaluation is suitable for assessing the disturbances caused by individual sources with a short duty-cycle. However, the combined effect of several disturbing loads operating randomly has to be taken into account for

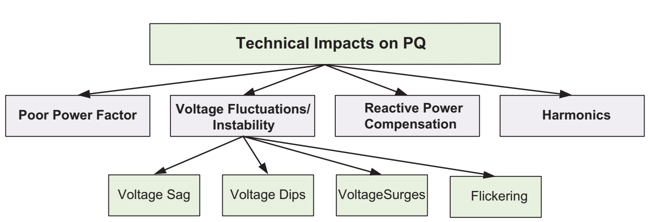


Fig. 14. Major potential technical impacts of integrating wind energy into the grid.

long and variable duty cycles. Hence, it is necessary to assess the long-term severity, P_{lt} which is derived from the short-term severity values over an appropriate period related to the duty-cycle of the load or a period over which an observer may react to flicker, e.g., a few hours, using Eq. (2) [79]:

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{N} P_{sti}^3}{N}} \tag{2}$$

where P_{sti} ($i=1,2,3, \ldots$) are consecutive readings of the short-term severity P_{st}.

The IEC flickermeter is in use worldwide for the evaluation of voltage fluctuation, harmonics as well as PQ [80]. Australia is an active participating member of the IEC's Technical Committee 77 on Electromagnetic Compatibility which developed IEC Standard 61000-4-15 [79]. Currently there are 38 participating member nations and 12 observer member nations on this particular technical committee [81].

The IEC Standard 61000-4-21 [82] provides a uniform methodology that will ensure consistency and accuracy in the assessment of power quality characteristics of grid-connected wind turbines. The power quality characteristics include wind turbine specifications, voltage quality (emissions of flicker and harmonics), voltage drop response, power control (control of active and reactive power) and grid protection and reconnection time. Flicker emissions are not only produced during switching or start-up, but also produced during continuous operation of wind turbines. The flicker emissions are produced during continuous operation due to variations in wind speed, the tower shadow effect and mechanical properties of the wind turbine [83]. A normalised measure of the flicker emission during continuous operation of the wind turbine is represented using Eq. (3) [82]:

$$c(\psi_k) = P_{st,fic}\,\frac{S_{k,fic}}{S_n} \tag{3}$$

where $P_{st,fic}$ is the flicker emission from the wind turbine on the fictitious grid, S_n is the rated apparent power of the wind turbine and $S_{k,fic}$ is the short-term apparent power of the fictitious grid.

A normalised measure of the flicker emission due to a single switching operation of the wind turbine is represented using eq. (4) [82]:

$$k_f(\psi_k) = \frac{1}{130}\,\frac{S_{k,fic}}{S_n}\,P_{st,fic}\,T_p^{0,31} \tag{4}$$

where T_p is the measurement period and the other parameters are as described above.

The harmonic currents shall be limited to the degree needed to avoid unacceptable harmonic voltages at the PCC. The IEC Standard 61000-3-6 [84] gives guidance for the summation of harmonic current distortion from loads and harmonic current at the PCC are estimated using Eq. (5):

$$I_{h\Sigma} = \sqrt[\beta]{\sum_{i=1}^{N_{wt}} \left[\frac{I_{h,i}}{n_i}\right]^{\beta}} \tag{5}$$

where N_{wt} is the number of wind turbines connected to the PCC, $I_{h\Sigma}$ is the *h*'th order harmonic current distortion at the PCC, n_i is the ratio of the transformer at the *i*'th wind turbine, $I_{h,i}$ is the *h*'th order harmonic current distortion at the *i*'th wind turbine and β is an exponent.

EN 50160 Standard [85] not only provides the regulatory guidelines for voltage parameters and their allowable deviation ranges but also defined the limits of harmonic voltages and total harmonic distortion (THD). Ranges of voltage variation, flicker severity, voltage dips, transient overvoltage and harmonic emission are defined by this standard. The THD is estimated using

Eq. (6):

$$THD_u = \sqrt[\beta]{\frac{\sum_{h=2}^{40} (U_h)^2}{U_1}} \tag{6}$$

In this section, influence of turbine types and other associated equipment on large-scale wind energy installations were explored with major observed technical challenges. Finally, the compatible standards required to analyse the observed challenges to ensure PQ of the power systems were focused upon.

With the increasing penetration of electricity production from wind power plants, it is essential to analyse the resulting impact of the integration of this green energy into the grid. The main PQ problems observed due to wind turbine technology, mechanical properties of wind turbines, variable characteristics of wind and grid connexion are the lack of control on the active and reactive powers which causes voltage problems, poor power factor and cause frequency deviations as well as harmonics injected into the network. Therefore, to ensure adequate PQ in the grid, it is a prime concern today to mitigate these problems and hence, substantial research, planning and development are required for increased integration of wind sources with the current power transmission and distribution networks.

In the next section, existing research that investigates the observed potential technical challenges with their mitigation techniques on integrating large-scale wind energy into the energy mix have been explored.

6. Research on impact analysis with mitigation techniques

It is no longer a question of whether to connect wind energy generation sources, but rather how much will be connected to electric transmission and distribution grids. The periodic and/or variable nature of wind energy production levels and characteristics of wind turbines and their grid connexion poses operational challenges for the transmission and distribution grid operators.

The power variation from wind turbines is very complex which decreases the PQ [10,73]. In addition to the problems of dynamic power fluctuations, another important issue is the voltage stability from connecting large amounts of wind power. Power electronic converters used in wind turbines are the main cause of harmonic current. With low levels of wind energy penetration, the overall effect on smart distribution system operations is limited, and if the penetration levels increase, more advanced control of the power system will be required to maintain system reliability which includes more efficient use of demand management response and intelligent energy storage; all of these can be enabled through the application of a smart distribution system [86].

Lin et al. [87] investigated the current and future developments of power systems and wind energy integration into the systems in Taiwan. The major challenges focused on the study are: wind turbine generators model, transmission planning criteria, renewable energy connexion standards, wind variability, system reliability and system operating costs.

In small-scale integration, the power system is assumed to have enough spinning reserve of active power that the frequency is able to be kept constant; therefore, only voltage problems are of concern. Induction machines demand reactive power from the network, which is partially compensated with shunt capacitor banks. However, lack of control on active and reactive power can disturb the voltage at the PCC and cause dynamic voltage variations. The dynamic voltage variations from the wind turbines during operation are quantified by flicker and step change [10].

Large-scale integration takes place under two main conditions: large wind farms connected to the transmission system, and several small wind farms connected to the distribution system in one area of the power system [10]. There are several issues arising from large-scale wind power integration including voltage stability and dynamic power oscillations during normal operation of the power systems. In order to achieve reliability, power systems must have reserves and controllers that can deliver the power when it is demanded. On the other hand, active controllers compensate the voltage and frequency variations, keeping the PQ within limits. Table 1 details the potential challenges of integration of wind energy into the grid.

Efficient design of power electronic converters for individual energy sources considering their physical and dynamic nature plays a key role in minimising the observed potential challenges and increases the efficiency of the system. The main purpose of power electronic converters is to integrate the distributed generation to the grid to maintain PQ standards. However, if the inverter is not implemented properly, high frequency switching of the inverter injects additional harmonics to the system that creates major PQ problems [77]. Appropriate design of electrical circuits with control systems mitigate voltage fluctuations, harmonic distortion and reactive power compensation, and thus ensure power factor and PQ improvements of the power system. New operational and optimisation tools are essential to play a key role in minimising load demand management, scheduling and despatching problems. Custom power devices such as shunt active power filters (static synchronous compensators - STATCOMs), static VAR compensation (SVC), series active power filters

Table 1
Potential challenges of integration of wind energy with the smart power grid [10].

Integration scale	Problems	Causes
		Large scale
Small-scale	Steady state voltage rise	Wind speed variation
	Over-current	Peaks of wind speed
	Protection error action	Peaks of wind speed
	Flicker emission during continuous operation	Dynamic operation of wind turbines
	Flicker emission during switching operation	Switching/start-up operation of generators
	Voltage drop	In rush current due to switching operation of generators
	Harmonics	Power electronic converters
	Power system oscillations	Inability of the power system controllers to cope with the power variations from the wind farm and loads
	Voltage stability	Reactive power limitations and excessive reactive power demand from the power system

(dynamic voltage regulators - DVRs), and a combination of series and shunt active power filters (unified PQ conditioners UPQCs) are the latest developments for interfacing devices between grids and consumer appliances. These devices overcome voltage/current disturbances and improve the PQ by compensating the reactive and harmonic power generated or absorbed by the load [77].

Research communities, industry equipment suppliers and utilities are working together to reduce the potential challenges and develop a sustainable power system worldwide. Only a few researchers have investigated the characteristics of observed problems and the correlation with possible causes. On the other hand, mitigation techniques to reduce or nullify these problems have been explored by a few other researchers. This part of the paper explores available research in this area.

Ibrahim et al. [57] explore the potential technical challenges with possible solutions of wind power systems that include variability of wind, power system operating cost and power quality. Authors concluded in [57], that the integration of the wind energy will be sustainable by using the power electronics equipment's to connect the wind turbine at the electricity grid; development of short and long-term energy storage technologies; development of hybrid systems, combining wind power with conventional and other renewable energy sources [57]. Ake Larsson presented the modelling and analysis of the flicker emission of wind turbines both for continuous [83] and switching [88] operations. These studies concentrated on the theoretical aspects of the flicker algorithm, wind turbine characteristics and the generation of flicker during continuous and switching operations of wind turbines. The flicker produced by each wind turbine during continuous operation was shown to originate from the wind speed, the tower shadow effect and the mechanical properties of the wind turbine. The required short-circuit ratio (SCR) caused by flicker under continuous operation increased with the square root of the number of wind turbines, while switching operations increased with a little more than the cubic root of the number of wind turbines. To evaluate voltage fluctuation and other PQ aspects, a comprehensive time-domain modelling of wind speed, wind turbine and flickermeter was proposed by Ei-Tamaly et al. [76]. They investigated the influence of different factors on voltage fluctuation caused by wind turbines. Their turbine model comprises sub-models of aerodynamic rotor, drive train and induction generator. From simulation results it was shown that voltage fluctuations were widely affected by the grid strength and ratio of grid internal impedance. A wind turbine's operating point and the Q–P characteristic of the generator indicate the point of minimum flicker emission, and flicker variation mainly depends on the wind turbine power curve [76]. The impact of wind speed, turbulence intensity, grid voltage quality and the number of turbines operating in a grid-connected system are investigated by Thiringer et al. [75] using fixed-speed stall-regulated wind turbines. Compared with the standard IEC-61000-4-21 [82], much high than expected flicker levels were observed in the experiments at low wind speeds which exposed a large number of voltage dips. Flicker emission increases with the increase of wind turbulence intensity. It was observed that the highest flicker emissions actually occur at low wind speeds, probably due to connexions of nearby wind turbines [75].

Studies show that voltage sag is experienced in the network due to the wind turbine high start-up current [83,89]. A constant voltage synchronous machine is preferable to an induction machine from the voltage sag perspective [90]. The level of affected customers in a given region of the network depends on the intensity of the sag and the network configuration [83]. Approximately $\pm 20\%$ power fluctuation has occurred for pitch controlled wind turbines with changes of ± 1 m/s wind speed [83]. However, power fluctuation is less for stall-regulated wind turbines. For a fixed-speed type wind turbine, approximately 30% of the total flicker is due to the tower turbulence [83,89] and flicker levels increased with the increase of wind speed. On the other hand, in the variable speed turbines, flicker levels decreased with the increase of wind speed. The impact of wind power generation on system stability with the determination of acceptable levels of wind power integration was investigated by El-Shilmy et al. [91]. From simulation results, it was observed that both the transient and voltage stability of the system are in a stable condition with a 24.55% wind penetration level and with SVC. However, the system became unstable in both transient and voltage stability at a 77.94% penetration level where it was found that SVC susceptance reached its upper limit and locked at that value which means the reactive power limits of the SVC had been reached. Therefore, the allowable wind energy penetration level for the system studied is less than 77% [91]. Eping et al. [92] investigated the impacts of wind generation on transient stability, considering three main aspects of wind generation that differ from conventional forms of generation. These were generator technology, location of wind generation and distributed generation. Results show that generator technology has a significant impact on transient stability; DFIG technology and converter driven synchronous generators are able to improve transient stability margins. Concentration of high wind resources in a localised area causes modified power flows as well as reduced critical fault clearing times. The penetration of wind energy into the sub-transmission and distribution systems introduces negative impacts on transient stability as the reactive contribution is highly limited due to reactive losses in sub-transmission and distribution systems [92].

Pedro Rosas [10] investigated the impacts of wind power on the power system, in particular wind power influences on the voltage stability, power system stability and PQ characteristics using dynamic simulation. Wind turbine technologies with power converters can actively control the reactive power consumption which increased the voltage stability of the power system. The study showed that a higher number of wind turbines smooth the power variations and reduces flicker phenomena. Characteristics of reactive power and voltage at the grid connexion point were evaluated through simulation analysis and it was observed that reactive power mostly depends on wind turbine power factor and active power output [93]. Results show that reactive power at the grid connexion point increases with the decrease of wind turbine PF. The reactive power outputs from wind turbines are higher than that required in transformers with the decrease of the active power output and hence the reactive power will increase at the grid connexion point and vice versa. Results also indicate that the voltage rises with the increase of reactive power at the grid connexion point and voltage falls when the wind farm absorbs the reactive power [93]. From the literature [77,94], it was shown that DFIGs are the most efficient designs for the regulation of reactive power and the adjustment of angular velocity to maximise the output power efficiency. These generators can also support the system during voltage sags, though this converter-based system injects harmonic distortion into the systems. However, the newly proposed Z-source inverter (ZSI) can mitigate the PQ problems for future DG systems connected to the grid [94]. In that study, a variable speed wind energy conversion system with a permanent magnet synchronous generator and ZSI are used to control the active power and harmonics as well as increase the reliability of system [94].

Characteristics of harmonics injected into a wind energy integrated power system were investigated with variety of configuration and operating conditions. Voltage distortion is expected to be observed in the distribution network due to the rotating machine characteristics [95] and the design of power electronic interface [96] in the wind energy systems which lead to harmonics in the

air-gap and, as a result, the stator and rotor will contribute to current harmonics. Harmonics are also observed in the main field passing over the stator slot due to the inherent characteristic of the machine; hence these are unavoidable [95]. A recent study [97] investigated the problem of a frequency converter in a wind energy system causing harmonics in the line current, leading to harmonic voltages in the network. With the application and guidance of regulatory standards IEC 61000-3-6 [84] and IEC 61000-4-21 [82], this study integrates several appropriate harmonic load models representative of harmonic network elements and harmonic sources. Potential voltage distortion was observed in the study [97] due to coincidence of the first harmonic resonance frequency with the peak harmonic spectrum of the wind turbine current. Results show that the harmonic distortion of the voltage is increased at minimum load as well as being more pronounced closer to the wind farm. A high voltage distortion appeared at the MV busbars which is a concerning issue, while there is minimal distortion at the HV side [97]. Muljadi et al. [71,72] explored the characteristics of self-excitation and harmonics generated by a fixed-speed induction generator used in wind turbine generation. The saturation of the magnetic circuit in the transformer and the resonance circuit between the capacitor compensation and the rest of the circuit causes harmonic injection that makes the power system vulnerable. The tap changer, capacitor compensator, the power factor, and the level of generation of the wind turbine all influence the intensity of saturation as well as the characteristics and amount of the harmonic source injection. Power quality behaviours, in particular voltage sags and harmonics injection into the network, were investigated in a study [98] on integrating wind energy into low voltage and medium voltage networks. Results showed low injection of voltage sags for all the three case study scenarios. Observed THD was within the safety limit as stated in the European standard EN 50160 [85]. However, THD increased with the increase of wind energy penetration into the system.

Advanced custom power devices with adequate converter and control systems such as SVCs and STATCOMs can mitigate voltage instability, reactive power problems and harmonic distortion as well as improve the PQ of the network. In order to enhance the terminal voltage quality, SVCs were used for reactive power compensation of wind power induction generators [99]. The use of STATCOMs with modified control strategies during normal and transient conditions has been addressed in [100] and [101] respectively. STATCOMs are superior compared to other flicker mitigation methods such as SVCs and series saturated reactors, STATCOMs being faster, smaller and having better performance at low voltage conditions [102,103]. STATCOMs are not always effective in regulating the voltage and reducing flicker emission while the wind turbine is connected to low X/R ratio or weak grids. Hence, Kasem et al. [64] used an efficient, limited rated electrolyser/fuel cell combination to control the ramp rate of the wind power and enhance the voltage quality at the PCC. This system avoids the frequent start-up and shutdown of fuel cell stacks and minimises the power flows in the electrolyser/fuel cell path. The system also capable of avoiding the impacts associated with directly grid-connected wind farms.

Power quality problems due to installation of wind turbines with the grid were explored by Yuvaraj et al. [104] with their mitigation techniques. A STATCOM based control mechanism is used to reduce the power quality problems on integrating wind energy into the grid. Simulation results show that an optimised STATCOM can cancel out the harmonic parts of the load current. The system is capable of meeting the reactive power demand from the wind generator and the load at the PCC to the grid, and maintaining the source voltage and current in-phase. This scheme improved the quality of power significantly and fulfilled the PQ requirement based on IEC 61000-4-21. The effect of a STATCOM on the low voltage ride through capability of a variable speed wind turbine with full scale converter during voltage sag on the grid side has been studied through simulation analysis [105]. From simulation results, it was observed that the STATCOM can considerably improve the voltage profile at the PCC by regulating the reactive power of the grid during faults and maintaining an appropriate level of voltage sag on the grid and prevents the turbine from being disconnected from the grid during certain levels of voltage sag on the grid side [105].

Hybrid battery-super capacitor energy storage systems are expected to be play a major role in power smoothing, power quality improvement and low voltage ride through in a wind energy conversion system. Research shows that hybrid battery-super capacitor energy storage regulates the voltage and frequency at the wind turbine output [59]. Kook et al. [106] developed a simulation model implemented using the Power System Simulator for Engineering (PSS/E) that explored potential mitigation techniques to reduce the level of impacts on integrating wind energy into the grid through application of an energy storage system (ESS). The ESS not only minimised the fluctuations from the wind power but also had a counteracting effect in the wind farm of any disturbances on the grid. Appropriate control by the ESS suppressed power fluctuations in the wind farm and improved the stability of the power system exposed to a high level of injection of wind power [106]. In another study, Muljadi et al. [72] investigated the impacts on interaction of wind farm, energy storage, reactive power compensator and the power distribution network with the changing of wind speeds. From simulation results it has seen that the voltage dip is as low as 0.91 p.u. in high wind power without any reactive power compensation. The authors used reactive power compensation to regulate the voltage of the network and verified the performances of the network with different types of compensator to select the optimum solution. The combination of fixed capacitor and static compensation is more cost-effective as the fixed capacitor is cheaper than static VAR compensation [72]. In the study, it was observed that the use of a 25-MVAR static VAR compensation and a 25-MVAR fixed capacitor at Bus 40 adequately compensated for the reactive power as well as voltage dips of the Tehachapi area during high wind. For the unity power factor operation of energy storage, a combination of 50 MW energy storage, a 25-MVAR static VAR and a 25-MVAR fixed compensator improved the voltage regulation significantly with $\pm 2\%$ of per unit voltage. On the other hand, for the rated current operation, the energy storage can be operated adequately with only a 50-MVAR fixed capacitor.

This section of the study highlighted the extensive research conducted to investigate potential technical difficulties and their mitigation techniques when integrating wind energy into the power system. Major potential technical challenges observed are voltage stability, power fluctuations and harmonics injected into the network. Efficient design of power electronic converters, adequate reactive power compensation and optimum design of wind turbines and the grid connexion all play a key role in minimising the observed potential challenges and increases the efficiency of the system.

The major findings of the study is summarised in the next section that the Government, policy makers, scientist and utilities can use as a guideline for large-scale deployment of wind energy for the future.

7. Discussion

- Wind energy has enormous potentialities and encourages interest worldwide for the large-scale penetration into the energy mix as it is free from the GHG emissions that cause global warming.

- It can assist to reduce the energy-crisis as well as the dependency on energy imports as it is abundant worldwide.
- Along with the significant positive environmental impacts, it has a few negative environmental impacts that include: impacts on social life, economical impacts, environmental impacts due to emission during installation and dismantling of wind farms and technical impacts that affect the PQ of the systems.
- The most significant adverse environmental impacts that affect residents of nearby localities are visual impacts, noise, interference with electrical equipment and the killing of wildlife.
- Research shows that observed social impacts are not significant and the amount of impacts are less compared to other sources of energy. Research communities and utilities are trying to minimise these problems by utilising new technology, equipment and converter systems.
- Wind energy has a high upfront cost due to its high capital costs and O & M costs. Most of the developers are not keen to invest these large capital costs. However, upfront costs are comparable to other energy sources after considering emission costs.
- Studies show that wind energy generation costs have been decreasing rapidly over time due to the introduction of new technology that has reduced the cost of turbines and other required equipment, improved integration techniques, smart grid technology and monitoring tools.
- Wind energy produces reasonable amounts of GHG emissions during the stages of manufacturing, transportation to the site, installation and future decommissioning, though it has no emissions during operation which is an excellent advantage considering global warming.
- Based on the outcome of LCA analysis, manufacturers and industrialists can reduce emissions from different stages of the wind energy generation life cycle that includes emissions from equipment by introducing new technology, transportation by boat and train instead of truck, improvements in the product manufacturing process in respect to emissions and implementing appropriate recycling processes.
- It can be concluded that, compared to other energy sources, wind energy has less negative impacts considering social, economic and environmental aspects. Therefore, it is a crucial issue today to quickly integrate large-scale wind energy into the energy mix. However, integration of large-scale wind energy while maintaining an adequate PQ is a challenging task.
- The major factors that influence PQ of the systems are: wind turbine design and types, nature of the wind resource and turbulence at the wind farm site, the position of the wind farm connexion to the grid, the characteristics of the grid and connected load types, plus the characteristics of the converters used in the wind farm.
- Most commonly used generators in wind farms are wound-rotor and permanent magnet synchronous generators, and squirrel-cage, wound-rotor and doubly-fed induction generators; all of them have advantages and disadvantages.
- Power quality not only depends on the design of generator/turbine types but also on availability of wind resources, electrical equipment, the grid connexion and grid quality.
- The potential technical difficulties that affect PQ of the network from these factors are: voltage fluctuation, power system stability, reactive power compensation, low power factor, harmonic distortion, energy storage, scheduling and forecasting, load management and synchronisation.
- Guidelines as well as International standards are developed by the IEC and other organisations to monitor the PQ parameters. The widely used standards in wind energy integration are IEC 61000-4-15 [78] and IEC 61000-4-21 [81].
- Substantial research, planning and development are being undertaken worldwide to reduce the observed challenges to ensure adequate PQ of the systems.
- Experimental and simulation study show that voltage fluctuations as well as flicker emission, sags and dips are observed due to the variation of wind speed or wind turbulence intensity, and these increase with the increase of wind speed variations. Voltage instability damages sensitive electric and electronic equipment and affects consumers getting a smooth power supply.
- Reactive power consumption by induction generator is a major problem and responsible for poor power factor, voltage and power instability in the network. DFIGs can regulate the reactive power efficiently.
- The saturation of the magnetic circuit in transformers, power electronic devices, non-linear equipment and capacitor compensators inject harmonics into the network which increases with the penetration of wind energy.
- Wind turbine technologies with efficient power converters mitigate voltage fluctuations, reactive power consumption, harmonic distortion and poor power factor as well as ensuring adequate PQ. SVC and STATCOMs are the most widely used devices that compensate for these potential technical challenges.
- Appropriate design and control of energy storage systems not only ensure the reliability and availability of power delivery but also improve the voltage stability and power system stability.

8. Conclusion

Wind energy harvesting is of prime interest today as it is the most promising RE source due to its clean, environment-friendly attributes. However, along with the positive environmental impacts, it has some negative environmental impacts as well that include: social environmental impacts such as visual, noise and death of birds; economic impacts as it has high upfront costs due to capital and variable costs; environmental impacts due to emissions during installation and future dismantling of wind farms, and technical impacts that affect the power quality of the network. This study conducted a comprehensive literature review to explore these potential impacts and their available mitigation techniques.

From this comprehensive literature review, it can be concluded that wind energy is not only climate-friendly and free from GHG emission but also has cost-effective and less negative social and environmental impacts compared to other sources of energy as technology is getting more efficient and cost effective. It has the potential to reduce the energy-crisis worldwide and create employment opportunities. Wind energy is now a mature technology and there is enough evidence in favour of large-scale wind energy firm. Research has been undertaken to minimise potential negative impacts of integrating large-scale wind energy into the grid for a sustainable power system for the future. Findings of this study are expected to be used as guidelines by the policy makers, manufacturers, industrialists and utilities for deployment of large-scale wind energy into the energy mix.

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